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TESTING OF SPACE SHUTTLE THERMAL PROTECTION SYSTEM PANELS UNDER SIMULATED REENTRY THERMOACOUSTIC CONDITIONS

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ABSTRACT

The advantages of maintaining a real-time computerized thermoacoustic testing system are demonstrated by results from space shuttle thermal protection system tests of Rene 41 and composite material panels.

INTRODUCTION

The mission profile and reuse of the space shuttle vehicle impose a severe acoustic fatigue problem for the design of the Thermal Protection System (TPS) for the orbiter. The orbiter TPS panel systems must withstand 100 flights and launch acoustics above 159 dB. Testing with high temperature and acoustic loading is required to qualify new materials and design configurations for the extreme environments which include orbiter reentry temperatures from 480° C to 1350° C. This testing must include detailed measurements of TPS panel behavior so that design changes required by development test or flight experience can be carried out systematically while maintaining minimum weight.

The Langley Research Center approach to the thermoacoustic fatigue problem is to test large "complete" structures and to simulate the environments (thermal and acoustic) as nearly as possible. Under this approach the theories or computations required to extrapolate from test conditions to service conditions are minimized as compared to approaches using more simplified environments such as equivalent-block loadings. The details of test control and data measurements are both highly controlled and extensively supervised under real-time executive computer control allowing maximum man/machine interaction.

The capabilities of Langley Research Center's new thermoacoustic fatigue apparatus for space shuttle thermal protection system (TPS) panel testing were presented in Reference 1. The purpose of establishing the thermoacoustic test capability was to develop and demonstrate workable test techniques which could be

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used in order to proof test TPS panels and provide diagnostic tools for the designer to "troubleshoot" his design in a complete, timely manner and to graphically illustrate to him during the test how his panel is performing.

Tests have been done in the LRC facility on two basic TPS panel system concepts, referred to as metallic and RSI (reusable surface insulation) panels. Both the metallic and RSI panels share the common characteristic of being composed of materials on which there is relatively little materials data and use experience. The designs are complex consisting of corrugated plates with elaborate standoffs and closure fairings to allow thermal expansion or a substructure to which is affixed a ceramic tile material by a heat-sensitive adhesive. The early LRC designed Rene 41 metallic TPS panel was used for two purposes: (1) to provide data on the behavior of a candidate metallic panel and (2) for developing the software, troubleshooting the hardware, and establishing the test methods which are described in this paper.

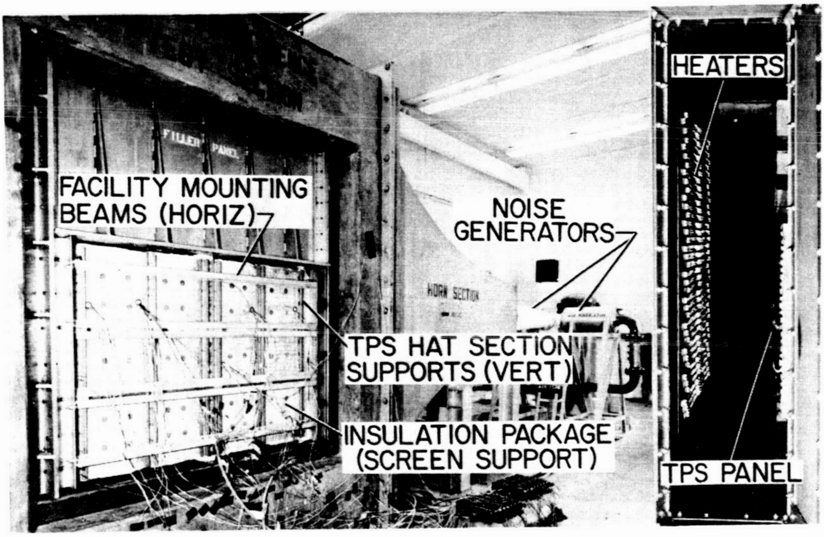
Data from actual tests of the metallic and RSI TPS panel are presented in this paper to demonstrate the effectiveness of the data systems employed and to illustrate how these methods may be used as diagnostic tools. Strain-gage response data and thermocouple data are included to illustrate damping effects of panel insulation, thermal profiles, and the effects of excitation level on panel response.

THERMOACOUSTIC FATIGUE TEST SPECIMENS

The TPS not only carries loads generated by the environment such as gravity loads, wind loads, engine noise and thermal and vibration inputs caused by passage through the atmosphere but also must withstand normal maintenance abuse. Since the TPS protects the entire vehicle from heat loads, it is a big factor in the vehicle weight and thus its weight must be minimized. Requirements for lightweight structures rule out drastic overdesign to meet acoustic requirements. Thermal loads in the range of 480° C to 1350° C during reentry dictate the use of exotic materials and complicated designs for the TPS. Descriptions of the expected TPS vibration and acoustic environments are included in papers by Schock (2) and Jones (3). Selection of the final vehicle configuration has fixed the expected maximum noise level in the range 159 to 168 dB rms overall. Several test TPS panels were selected by LRC as a part of the research program in support of the space shuttle development. The test panels were fabricated from a variety of exotic materials and represented a range of designs. Two of these designs are described here and test results for these TPS panels are presented in this paper.

Metallic TPS

The installation of the Rene 41 TPS panel in the LRC thermoacoustic fatigue facility is shown in Figure 1. The panel is supported by longitudinal steel facility mounting beams which are attached to the six vertical stainless-steel hat section stringers shown in Figure 1. The insulation package which covers the rear of the panel is attached to a wire mesh screen and is held in place by the standoff/hat section interface which is a bolted joint. The panel was fabricated from 0.04 cm thickness Rene 41, 1.486 m long by 1.072 m wide plate and was supported by four transverse standoff systems and 14 individual standoffs across the center of the plate as shown in Figure 2. The standoffs were of sufficient height to allow installation of a 7.6-cm-thickness fiber-type insulation package. This panel was a very



EXTERIOR TEST SET UP VIEW

INTERIOR TEST CHAMBER VIEW

Fig. 1–(left) Test setup for a Rene 41 TPS panel showing facility and TPS support members and rear view of insulation package. (right) Interior test chamber view showing heaters and TPS panel.

early LRC design described in papers by Dixon and Shore (4), and Dowell (5) and Stein, et al. (6).

RSI TPS

The RSI concept tested consists of graphite-epoxy laminate installed on a glass-phenolic honeycomb core panel and supported on aluminum extrusions along its sides. The 1.9-cm-thickness subpanel was protected with a 1.52-cm-thickness RSI composed of mullite ($3Al_2 \cdot 2\ SiO_2$) fibers with ceramic fillers and binders and was glazed with an external vitreous coating. The RSI tiles are bonded to the subpanel with an elastomeric adhesive. The elastic modulus of the vitreous coating was 0.37 times that for aluminum and the RSI has a modulus only 0.0018 that of aluminum. The test article consists of one 66-cm-wide by 76-cm-long TPS panel and partial panels at each end to bring the total length to 1.07 m.

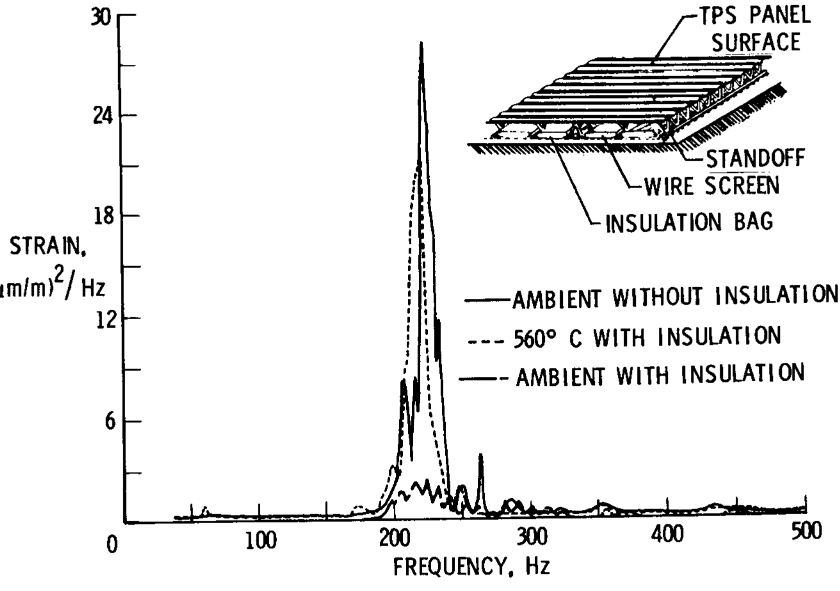


Fig. 2–Linear mean square spectral analysis using strain response data from 560° C and ambient temperature tests of a Rene 41 TPS panel shown in inset, which demonstrate the damping effects of insulation and further effects of thermo-acoustic excitation at 145 dB.

TEST PROCEDURE

The basic test conditions for these tests are described in Reference 1. The major elements of the test program which demand emphasis for the purpose of this paper are the following:

1. Extensive data must be taken rapidly to determine modal response and correlation with theory or previous work and yet avoid damage to the panel and instrumentation.
2. Extensive thermal data must be gathered quickly in order to evaluate heating distributions so they can be altered during the test if necessary and over heating may be avoided.
3. Mission cycles during failure testing must be simulated in order to best represent service conditions and prevent both over and under testing due to test technique.

Metallic TPS

This panel was tested at ambient and 560° C for both response and mission simulation conditions. The panel was rated for 816° C and was used in the development of the computer software controlling the mission cycling since there was no danger of over heating the panel. Response tests were of very short duration at 145 dB rms overall continuing for approximately 5 minutes to allow analog tape recording to data. Digital data acquisition required less than 1 minute of testing time. Mission cycles were defined as 30 minutes at continuous acoustic loading and at the beginning of the cycle the panel was heated for approximately 18 minutes. The panel was held at its maximum temperature for about 9 minutes and was heated and cooled at a controlled rate as shown in Figure 3 (curve A). During 86 cycles at 150 dB overall rms and nine cycles at 158 dB overall rms, the panel was inspected visually at least once each five cycles in order to detect failure. During the nine cycles at 158 dB the temperature dropped to 510° C due to increased airflow at the higher noise levels.

RSI TPS

The test sequence for this panel was similar for testing of the open section corrugation TPS, but greater care was required in heating the panel. The adhesive which bonds the RSI to the subpanel is rated for only 177° C and therefore when temperatures in excess of 177° C are applied they must be time limited. The time lag through the insulation must be evaluated in order to peak the temperatures at the bond line appropriately

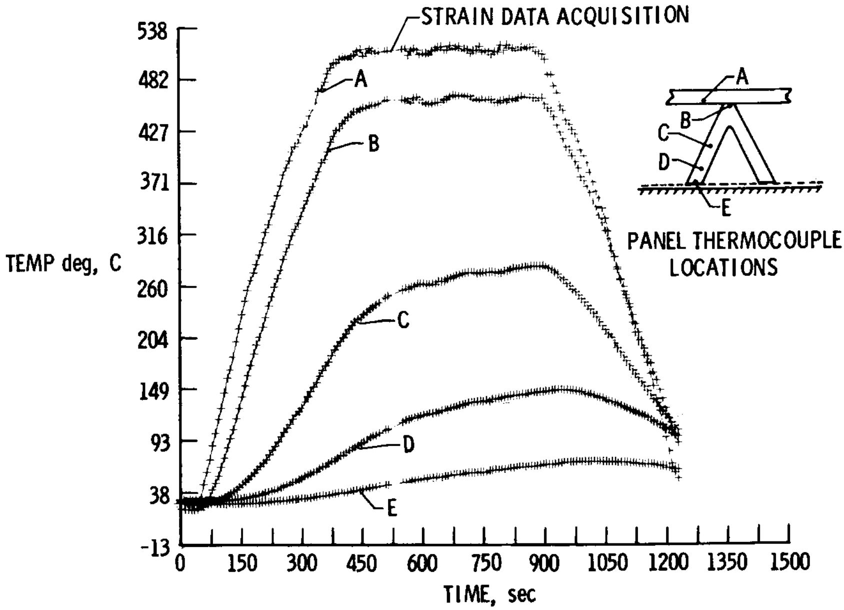


Fig. 3—Demonstration of thermal time history and strain acquisition capabilities by presentation of five of 32 sequentially logged thermocouples and indication of time during which 15,000 points for each of 18 strain gages were digitized for a Rene 41 TPS panel. Thermocouple locations on standoff are shown in inset.

and avoid over or under testing of the panel. Since the insulation on this panel was not removable, subpanel response was not evaluated separately. Tests reported herein included only ambient temperature response tests.

TEST INSTRUMENTATION

Each of these TPS panels was extensively instrumented with strain gages and in addition the RSI panel was instrumented with nine accelerometers. One of the reasons for the metallic panel test was to evaluate strain gages and establish effective instrumentation systems. Chromel alumel thermocouples were used extensively in order to monitor the temperature and a selected thermocouple channel was used as a feedback element during mission cycle to establish test control through the digital computer.

Metallic TPS

This panel was instrumented with 18 strain gages and 32 thermocouples. Seven strain gages were located on the longitudinal center line of the panel. Adjacent to the transverse panel center line in the upstream bay, six gages were located on the bay center line and five gages were located on the center line of the corresponding downstream bay (upstream is used to indicate the position nearest the noise source) including one each on the panel longitudinal center line. The strain gages were distributed in representative locations to allow interpretation of mode shape through cross spectral density analysis where signal quality is good and panel response is regular (i.e., where symmetry of response is maintained and corresponding panel segments respond similarly). Eight thermocouples were installed on the longitudinal panel center line, 11 thermocouples were an integral part of free filament strain gages, nine thermocouples were located on two standoffs (arrangement is shown in Fig. 3 for one standoff) and four thermocouples were embedded in the insulation package. The 0.95-cm-length welded strain-gage response is analyzed to provide the data in Figure 2 and was located on the panel longitudinal center line, 9 cm from the upstream rivet line of second bay downstream (54.5 cm from the upstream edge).

RSI TPS

Thirty-eight strain gages and 27 thermocouples were installed by the manufacturer of this TPS. Eleven thermocouples are constructed as an integral part of the high temperature free filament strain gages. Twenty-seven of the gages used on this panel are conventional foil gages as the adhesive's limitations required the remaining structure to be below 177° C. Instrumentation is installed at four depths in the panel: (1) the RSI surface, (2) the bond line, (3) the honeycomb panel backface, and (4) the face of the aluminum extrusion to which the panel is attached. Most of the instruments on the RSI surface (strain and temperature) failed during the first test sequence due to poor adhesion of the gage to the RSI's vitreous coating. Nine accelerometers are also bonded to the back face of this panel and are located at the intersection of lines which divide the basic TPS panel into nine equal 19-cm squares. The accelerometers are low mass piezoelectric devices. Data from these devices were used in conjunction with microphone measurements at the corresponding spatial locations to determine the transfer functions of the panel (i.e., the input/output relationship of the acoustic field and the panel vibration response).

DATA ACQUISITION

Basic data acquisition capabilities are described in Reference 1; however, changes made after July 1972 have added considerably to the speed and flexibility of the system. Spectrum analysis and plotting as shown in the figures can be accomplished in less than 3 minutes. The number of possible input/output interfaces was increased from 32 to 45. Increased capability was achieved by adding a 32K word memory computer to the system.

Figure 3 illustrates data obtained during computer control of the experiment and data acquisition. Figure 3 shows five of 32 thermocouple measurements that were taken each 7 seconds by the computer system and stored for later plotting as shown. There are a number of switch options including tabulation of the temperature data on a teletype during the test. One thermocouple is designated as control and in this test an exterior thermocouple such as "A" in Figure 3 is used to increase and decrease the temperature 2.2^{o} C per second in order to simulate reentry. Acquisition of strain-gage data took place during the gap in temperature measurements which can be seen in each of the profiles in Figure 3 (+ symbols on plot indicate temperature measurement). During the gap shown in Figure 3, dynamic strain-gage data were digitized for a total of 15,000 measurements for each of 18 strain gages (30 transducers including microphones and accelerometers were digitized in earlier runs). Digitization of the 270,000 points required only 6 seconds with other elements of the program accounting for the additional time. Analysis of the strain-gage data was accomplished by a second program used after testing of the panel was complete. The new computer improved the speed of the analysis program by a factor of 4 or greater making it feasible to do on-line corrections using the analysis as a feedback element.

TEST RESULTS

The tests discussed in this paper marked the first time thermoacoustic tests had been run on structures of this size and complexity with both thermal and force inputs, the test adjustment taking place under real-time computer control. Results to date demonstrate that automated control of thermoacoustic tests are both practical and efficient. A lack of analytical results for the complex structures presented here prevented maximum use of these real-time test results which can be powerful design tools where the designer can interact directly to make immediate interpretations of the test results to optimize testing.

Metallic TPS

The results of a welded gage response along the panel longitudinal center line is expressed as strain in dimensionless amplitude squared per unit bandwidth versus frequency in Hz in Figure 2. Three panel conditions are compared in Figure 2. It can be seen from Figure 2 that addition of the insulation reduces the acoustic response of the panel considerably. During later thermoacoustic excitation, however, Figure 2 shows the effects of previous insulation damping almost entirely eliminated. All three curves are for the same nominal 145-dB rms overall random noise whose spectrum is similar to that presented in Reference 1.

The panel in Figure 4 is labeled to show the temperature distribution across the plate. The upstream and lower edges of the panel are slightly cooler due to adjacent steel members used as facility supports which act as heat sinks. The aluminum filler panel on the upper edge (see Fig. 1) stabilizes in temperature more rapidly while the downstream edge benefits from air heated across the panel and a narrow aluminum filler/support member. The panel which is about 60 cm from the heaters is heated to temperatures about 80° C higher when no air is flowing.

When response testing was concluded this TPS was subjected to a simulated mission where a 150-dB random noise excitation was maintained for 30 minutes, and during that time the thermal profile illustrated in Figure 3, curve A, was applied. Figure 3 shows the temperatures measured on the panel and a standoff in the center of the panel. It can be seen that the time from the beginning of heating until the termination of heating was about 1200 seconds. The upper surface of the insulation blanket was approximately at the elevation of point C on Figure 3 and the maximum temperature of this side of the insulation was 253° C. The back-side temperature of the insulation package was 28° C at peak heating. The thermal data were used to control the thermal loading and to evaluate the performance of the insulation package.

The change of the TPS response as a function of time during mission cycling is illustrated in Figure 5. Figure 5 is a spectrum level plot of strain in dB versus frequency in Hertz for cycles number 2 and 86. The sound level was raised to 158 dB

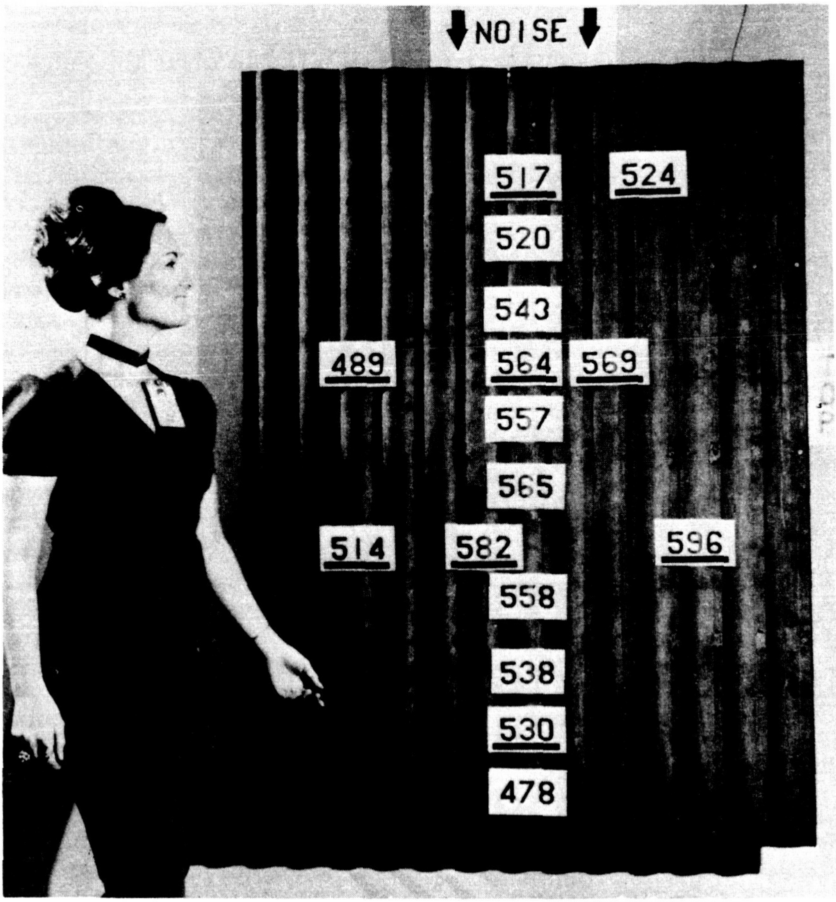


Fig. 4—Heat distribution on a Rene 41 TPS panel as recorded during test and printed on teleprinter. Temperatures in ^{o}C are centered on thermocouple locations. Numerals underlined indicate thermocouples which were on the lower surface of the panel as shown.

and heating correspondingly reduced to 510^{o} C on the 87th cycle and panel failure as pictured on Figure 6 was detected after the 95th cycle. Figure 5 shows that the overall strain response has increased in the region from 50 to 150 Hz and also from 300 to 500 Hz and also shows a downward shift in the resonant frequencies.

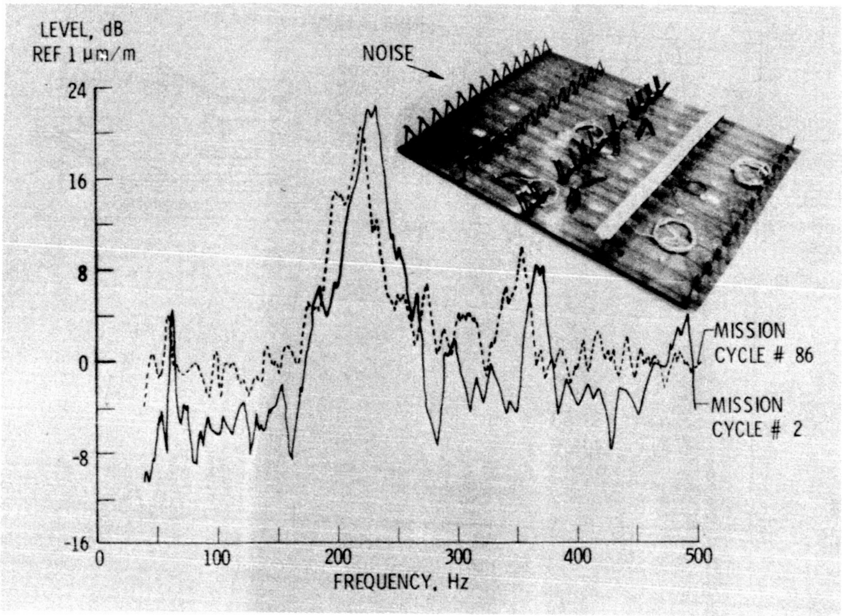


Fig. 5–Illustration of the change in strain response of the Rene 41 TPS panel between the second mission cycle and the 86th mission cycle during combined 150 dB random noise and 560° C heating. After nine additional cycles at 158 dB random noise and 510° C heating, the panel failed as shown in inset.

The inspection of this panel for failure was difficult and only visual inspection was used. Most failures (except for the popped rivet which was recognized) could not have been detected without disturbing the insulation or disassembly of components.

It is probable that failure occurred by the 86th cycle. If a standoff had broken off and "rattled around" it could be expected to build up the high-frequency content of the response much as is shown by the buildup of energy in the 300- to 500-Hz range in Figure 5. When as many standoffs had broken as were finally detected there should also be a buildup in the low-frequency end due to the plate randomly "floating around" much as we see in the 50- to 150-Hz range in Figure 5. These effects, of course, cannot be verified for this test but one can readily see from this illustration how knowledge of these differences during a test might benefit the test conductor.

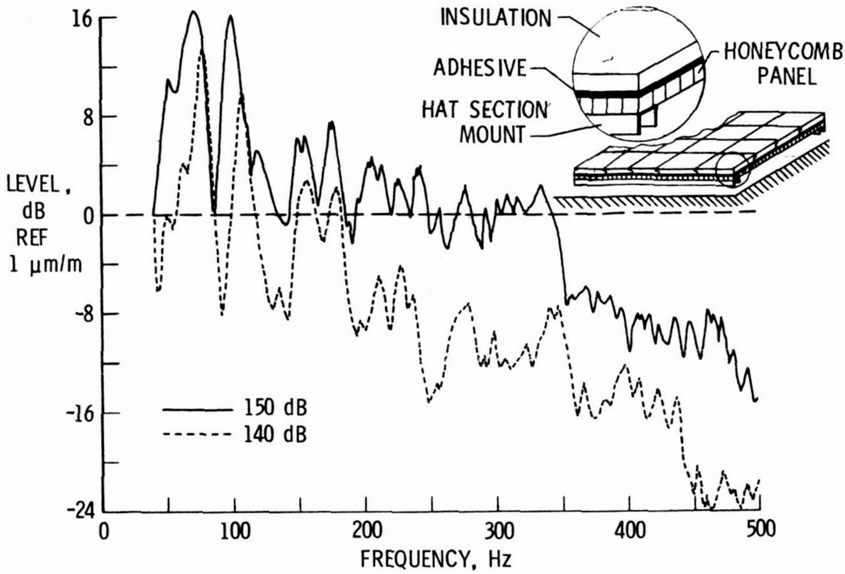


Fig. 6—Demonstration of log amplitude plot of strain spectrum level with linear frequency scale using strain response data from a reusable surface insulated graphite/epoxy honeycomb panel shown in inset.

RSI TPS

Results of ambient temperature tests of the RSI panel at acoustic excitation levels of 140 dB rms overall and 150 dB rms overall are shown in Figure 6. Figure 6 data are spectrum level plots of strain in dB versus frequency in Hz for a centrally located strain gage located between the RSI bond line and attached to the subpanel surface. A sketch of the RSI panel is shown in the insert of Figure 6.

The two peaks in Figure 6 near 100 Hz shift down in frequency slightly and become wider when the acoustic load is increased from 140 dB to 150 dB. The broadening peaks indicate an increase in damping. The acoustic loading has increased by a factor of 3.16 and the overall rms strain increased from 10.84 to 23.32 μm/m. It is perhaps important to note that a pseudo-random noise generator is used as the signal generator and that the details of the spectrum do not change significantly in the range of 40 to 500 Hz. When the level is increased from 140 dB to 150 dB these results indicate nonlinear behavior of the RSI panel. Thermal profiles similar to those in Figure 3 were recorded for this panel but are not shown. Thermal loading was minimized to prevent bond-line damage and as an illustration of control problems, a 120-second duration heat pulse peaked at the bond line about 120 seconds after heating of the panel surface was terminated.

Instrumentation Performance

Welded strain gages were found to be particularly good from the standpoint of signal quality and endurance. The primary disadvantages of welded gages were their cost and stiffening effects of their stainless-steel cabling where this is a problem. Free filament gages installed with aluminum oxide were also used with good experience and there were few failures of the gages themselves but wiring endurance was poor.

During tests of the metallic TPS system the welded strain gages endured the environments of high temperature and acoustics extremely well. Only two welded gages have been failed during testing and these failed during the 87th cycle of the single corrugation TPS. The difficulty with the free filament gages is not so much the gages themselves as the wiring of these gages. More than half of the free filament gages were failed after 30 minutes of combined environments and 90 percent of the gages were failed by the 86th cycle of the single corrugation TPS. Thermocouple life was only slightly better than that for strain gages but a variety of types were not evaluated.

Materials Performance

The Rene 41 material was not heated to its design temperature of 816° C short-term use but combined environments were adequate for failure. The Rene 41 standoff system failed extensively as shown in Figure 5. The upstream row of standoffs failed prior to failure of the individual standoffs in the center. A "popped" rivet head at the center line was the first observed failure but abrasion of the upstream standoff caused by rubbing against the insulation support screen indicated failure began in the upstream standoff. Under the testing ground rules established for the single corrugation panel inspection at the mount/standoff interface was not possible due to the presence of the insulation. Early detection would not have been likely without frequent disassembly of the panel.

The RSI tests have not progressed into mission cycling at this writing but virtually all strain gages that were attached to the vitreous coating on the panel surface have delaminated possibly due to a silicone residue on the coating.

CONCLUSIONS

A thermoacoustic fatigue facility of the type used for experiments described in this paper is an extremely useful tool for use in the design process and for proof testing TPS structures. It is shown that computerized test control and real-time data acquisition are important in evaluation of complex structures of the type described in these tests.

The metallic TPS tests represented a unique step forward in the state of the art of thermoacoustic testing as it represented the first time structures of this size were subjected to combined environments under such detailed computer control and in which strain and thermal data were so extensively and efficiently obtained and analyzed. A number of phenomenological illustrations were presented as evidence of this capability including the effects of damping in reducing panel response during initial response tests caused by insulating the panel. It was shown how thermal loading was carefully controlled and how profiles are easily compiled for comparisons. The need for rapid data evaluation was demonstrated by showing the changes in response between mission cycle number 2 and mission cycle number 86. Buildup of the high-frequency response between 300 to 500 Hz which may have been indicative of standoff failure and the resulting vibration of the cantilevered strut was pointed out. The later buildup of response between 50 to 150 Hz may have been indicative of increased motion of the "unsupported" plate. The decline in frequency of the primary modes are supportive of the previous interpretations. The rapid analysis capability that is now a part of our capability would have been a potentially useful tool in detecting early failure of the TPS panel, which in these tests was failed extensively.

The RSI TPS data presented for excitation levels of 140 dB and 150 dB represent only initial data from continuing thermoacoustic tests. An increase in damping of the two lowest frequency primary response peaks due to increased loading is illustrated from these early tests on the RSI structure.

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